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Application of Modified Profile Analysis to Function Testing of Simulated CTOL Transport Touchdown-Performance Data

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SUMMARY

This paper describes two applications of a recent modification to the methodology of profile analysis. The modification permits the testing of differences between two functions as a whole rather than point by point and with a single test rather than multiple tests. This modification is applied to separate examinations of the effects of two visual display systems and two sets of force-feel characteristics on pilot-simulator performance of transport approach, flare, and touchdown.

The first application was to a flight-simulation comparison of pilot-vehicle performance with a three-element refractive display to performance with a more widely used beam-splitter—reflective-mirror display system. The results demonstrate that the refractive system for out-the-window scene display provides equivalent performance to the reflective system.

The second application demonstrates the detection of significant differences by modified profile-analysis procedures. This application compares the effects of two sets of pitch-axis force-feel characteristics on the sink rate at touchdown performance utilizing the refractive system. This experiment demonstrates the dependence of simulator sink-rate performance on force-feel characteristics.

INTRODUCTION

The purpose of most flight-simulation experiments is to detect differences in the performance of the man-vehicle system under investigation as certain factors in the experiment are varied. Often the performance index of interest may be expressed as a function. Most instances of statistical treatment of such data are in terms of multiple tests at succeeding values of the independent variable. A recent modification by Myers (ref. 1) of a statistical methodology utilized in multivariate analysis allows for the testing of functions with a single test rather than multiple tests. The modification is made to the methodology of profile analysis (ref. 2) and provides a significant tool to the simulation researcher. Ambiguous aspects of conventional techniques, such as how many points must be significantly different to declare the functions different, are eliminated.

Myers develops the statistical procedure in detail and addresses the power of the test and its implication on experimental design in reference 1. The present paper discusses the application of the analysis procedure to flight-simulation experiments of current interest.

Some of the factors affecting the quality of a flight simulator are the mathematical model of the flight vehicle and its environment, the cockpit hardware, the force-feel characteristics, and the motion, aural, and visual cues provided to the pilot. Although the general quality of current conventional

take-off and landing (CTOL) simulators is thought to be high, performance deficiencies are present, and particularly evident, in the regime of flare and touchdown control. The significance of these deficiencies is increased as more reliance is placed on flight simulators for pilot training and proficiency maintenance.

The deficiencies in the past have been attributed to each of the previously mentioned factors (ref. 3), with current emphasis falling on the motion factor (ref. 4) and, more commonly, on the visual factor (refs. 5 and 6). A portion of this paper addresses the visual factor and will present the objective and subjective data collected during the fixed-base evaluation of a refractive-lens display system that is described in reference 7. The system presented a terrain model-board view of the out-the-window scene to the pilot of a 737-100 simulator during approach, flare, and touchdown. The results of this evaluation study will be compared via modified profile analysis to the results of a previous moving-base study utilizing the same simulation model and pilots, but with a different display system (a reflective optics system) and a different cockpit (ref. 6).

Differences between the cockpits were minimized in order to compare pilot-vehicle performance with the two different visual display systems. Static viewing of an airport scene through the two systems had suggested that different height cues were provided by the systems. However, no consistency in the different height estimates made by subjects viewing both systems was found. Some subjects gave higher estimates at certain altitudes with one system and lower estimates at other altitudes. The only consistency found was that differences existed between estimates at the same altitude for the two systems.

Also, a separate evaluation was conducted for two sets of damping and gradient parameters of the pitch-axis force-feel characteristics, utilizing the refractive-lens display system. Modified profile analysis is also applied to these force-feel dependent results.

In each of the aforementioned applications of the statistical method, the sink rate at touchdown as a function of trial number (i.e., learning curves) is the chosen performance measure for each set of simulator characteristics. After describing the simulator characteristics of the two studies, a brief discussion of the methodology of modified profile analysis will be presented. The two applications of the procedure will then be discussed.

THE FLIGHT SIMULATOR AND LANDING TASK

The commonalities and the differences existent during both studies are presented in the following paragraphs.

Characteristics of the Airplane Mathematical Model

The mathematical model of a 737-100 airplane included a nonlinear data package for all flight regions, a nonlinear engine model, nonlinear models of

servo actuators, and spoiler mixers. The simulation of the basic airframe was well validated prior to its use in numerous studies.

For the subject studies, the simulated airplane was in the landing-approach configuration with the flight characteristics as approximated in table I. The manual mode was used for flight control rather than modes such as control-wheel steering, navigation, or autoland.

Cockpit Configuration in Previous Study

The study of reference 6 utilized a moving-base cockpit with a reflective display system.

Moving-base cockpit.- The Langley visual motion simulator (VMS) cockpit was configured as a transport cockpit. The primary instrumentation consisted of an attitude-director indicator (including steering commands without flare guidance), vertical-speed indicator, a horizontal-situation indicator, altimeter, airspeed indicators (both indicated and true), angles of attack and sideslip meters, and a turn-and-slip indicator.

The control forces for wheel, rudder pedals, and column were provided by a hydraulic system coupled with an analog computer. The system allows for the usual variable feel characteristics of stiffness, damping, coulomb friction, breakout forces, and inertia. The force gradients were provided by the digital computer used to solve the airplane mathematical model. Selection of the parameter values of the control-loading system was included in the extensive validation process for the 737-100 flight simulator.

The nonlinear, coordinated, adaptive washout method (refs. 8 and 9) which was developed at Langley was used to provide motion drive signals to the six-degree-of-freedom moving base (refs. 10, 11, and 12). The adaptive washout filters of this washout method are based on continuous, steepest descent, optimization techniques. Table II presents the performance limits of the motion base, although conservatism must be exercised in the use of the position limits, since these limits change as the orientation of the synergistic base varies. Motion was restricted to five degrees of freedom because objectionable hydraulic noise is induced by the heave motion of the synergistic base, and only a small amount of vertical cue was available anyway. The small amount of vertical cue available is due to a combination of position limits of the motion base and the short-period frequency of the 737-100 airplane in the landing-approach configuration. The cue available for heave under these conditions is less than 0.05g, which is the product of amplitude, 0.4572 m, and frequency squared (frequency is less than 1 rad/sec). The heave axis was, therefore, used only to present touchdown cues.

Reflective display system.- An out-the-window virtual image system located nominally 1.27 m from the pilot's eye presented a nominal field of view 48° wide by 36° high of a 525 television line raster system and provided a 46° by 26° instantaneous field of view.

The system supplies a color picture of unity magnification with a resolution on the order of 9 minutes of arc. The virtual image system was the beam-splitter—reflective-mirror type illustrated in figure 1.

Cockpit Configuration in Present Study

The present study utilized a fixed-base cockpit with a refractive-optics display system.

Fixed-base cockpit.- The Langley transport simulator cockpit was used during this study. The primary instrumentation was essentially identical to that of the prior study (ref. 6) conducted in the VMS. The control forces on wheel, column, and rudder pedals were provided by a hydraulic system coupled with an analog computer, a system similar to that of the VMS. The control forces were identical to those used in the VMS study for the first portion of the study. Thus, an effort was made to make the only variables existing between the two studies be the differences in the visual display systems and motion—no-motion conditions. The results of earlier work on the VMS with the same airplane simulation (ref. 13) reported no significant effects from the addition of motion cues during CTOL approaches. (Heave motion was omitted also during this prior study.)

Refractive display system.- An out-the-window virtual image system, utilizing the triplet-lens design of reference 7, presented the same approximate field of view and resolution of the 525 television line color scene of the terrain board as the reflective display system. This lens design is illustrated in figure 2.

Force-feel characteristics.- The pitch-axis force-feel characteristics for the first portion of the current study, which were identical to those used in the VMS study, were changed considerably for the second portion of the study. The contrast between the two sets of parameters is shown in table III.

Visual-Scene Generator

The visual-scene generator consists of a television-camera transport system used in conjunction with a terrain model board. The model board, 7.32 m by 18.3 m, offers terrain and airport complexes at a 750:1 scale and a 1500:1 scale, complete with taxi lights, visual approach slope indicators (VASI), runway end identifier lights (REILS), and so forth. Provision is made for day, dusk, and night scenes, including airplane landing lights during night landings. Since most of the data available from the VMS study was taken on the 0.914 km runway on a 750:1 scale during daylight operation, the same conditions were used in obtaining the additional data for the current study.

The approximate second-order tranfer-function parameters for the camera transport system are presented in reference 14 and show translational lags of 10 msec or less and rotational lags of 20 msec or less.

Approach, Flare, and Touchdown Task

The simulated airplane was trimmed straight and level at an airspeed of 120 knots on the glide slope and localizer at a range of 3.22 km from the runway threshold. The aim point on the runway was 305 m beyond the threshold. The pilot's task was to effect a transition from straight and level flight to the 3° glide slope; then, while controlling speed, the pilot would complete the approach and then flare visually and touch down.

Participating Pilots

Four NASA research pilots participated in each of the landing studies. Two of the pilots have had extensive experience with visual landings in flight simulators, whereas the other two have had only limited experience.

MODIFIED PROFILE ANALYSIS

The methodology developed in reference 1 was used in order to test for statistical differences between sink rate as functions of trial numbers for both the two displays and the two force-feel conditions. The methodology is described here as applicable to only two functions, although reference 1 treats the general case as well.

Function Construction

The sink-rate functions were constructed by obtaining the mean sink rate for groups of five touchdowns in chronological order by groups for each condition. Thus, the first five landings made up the first group mean, the sixth through the tenth landings made up the second group mean, and so forth. Each condition was replicated 30 times by various numbers of pilots, yielding six group means for each function.

The Methodology

In presenting the methodology, let

$$\vec{y}_i = \left[y_{ij}\right] = \begin{bmatrix} y_{i1} \\ y_{i2} \\ \cdot \\ \cdot \\ \cdot \\ y_{is} \end{bmatrix} \qquad \left(i = \begin{cases} \text{Condition 1} \\ \text{Condition 2} \end{cases}\right) \qquad (j = 1, 2, \ldots, s)$$

where s is the number of trial grouping (6) and y is the sink rate. Thus, $\vec{y}_1$ is a vector consisting of the function values, sink rate, at each trial group, for condition 1. It is assumed that this vector, and $\vec{y}_2$ as well, follows a multivariate normal distribution with common variance-covariance matrix Σ, which is an $s \times s$ matrix. The practical implication here is that within each function, the observations are correlated and the correlation structure is the same for each of the two functions.

Now replicate each function (or vector) η_1 and η_2 times, respectively. It is desirable to test the null hypothesis

$$H_o : \vec{\mu}_1 = \vec{\mu}_2$$

where $\vec{\mu}_i$ is the vector of the true means for the ith function.

Let $\hat{\Sigma}$ be the estimate of the variance-covariance matrix Σ obtained by pooling the sample variances and covariances for each function over functions, and let $\bar{\vec{y}}_i$ be the vector of means.

Then, the equation

$$T^2 = \left(\bar{\vec{y}}_1 - \bar{\vec{y}}_2\right)' S^{-1}\left(\bar{\vec{y}}_1 - \bar{\vec{y}}_2\right)$$

where

$$S = \left(\frac{1}{\eta_1} + \frac{1}{\eta_2}\right)\hat{\Sigma}$$

follows Hotelling's T^2-distribution with $(\eta_1 + \eta_2 - 2)$ degrees of freedom. (See ref. 1.) The statistic $\dfrac{(\eta_1 + \eta_2 - s - 1)}{(\eta_1 + \eta_2 - 2)s} T^2$ follows an F-distribution with s and $(\eta_1 + \eta_2 - s - 1)$ degrees of freedom. This fact allows testing of the null hypothesis of equality of mean vectors by using the upper tail of the F-distribution. If $\vec{\mu}_1 \neq \vec{\mu}_2$, the test statistic follows the noncentral F-distribution (ref. 2) with $(s, \eta_1 + \eta_2 - s - 1)$ degrees of freedom and with the noncentrality parameter

$$\delta^2 = \frac{\eta_1 \eta_2}{\eta_1 + \eta_2}\left(\vec{\mu}_1 - \vec{\mu}_2\right)' \Sigma^{-1}\left(\vec{\mu}_1 - \vec{\mu}_2\right)$$

Thus, the estimated power of the test may be calculated for a specific difference $\vec{\mu}_1 - \vec{\mu}_2$ and for an estimate of Σ.

EXPERIMENTAL RESULTS

Comparison of Visual-System Data Sets

In order to obtain a subjective comparison between the effects of the two systems on landing performance, each of the four pilots involved in the previous study was allowed to refamiliarize himself with the characteristics of the old system by making several approaches and landings in the VMS simulator with the reflective display.

Due to scheduling problems, two of the pilots were unable to complete the full set of consecutive landings with the refractive display system. Thirty approaches and landings were completed by each of the other two pilots. Subjective data were obtained from all four pilots both for the approaches and for static viewings. The pilots felt that there was a difference in height cues between the two systems when viewed statically. However, none of the pilots felt that there was any dynamic visual difference between the two display systems or between their performances with each system.

Figure 3 depicts the mean sink rate at touchdown and the standard deviations for groups of five touchdowns in chronological order by groups for the two display systems. The known factors involved in this comparison are the motion—no-motion conditions and the reflective-refractive display systems. Another factor could have been pilot variability, since data from four pilots were used for the reflective display. However, t-test results indicated no significant differences between the mean performance for the reflective display of the two pilots completing all runs, the two pilots who completed only the reflective runs, and the means of all four pilots.

As mentioned previously, the motion factor was not felt to be a strong contributor, especially since a heave cue (considered to be critical in ref. 4) was not presented. Conventional statistical analyses were utilized in addition to modified profile analysis. Table IV presents the statistical analyses of the means (t-tests) and standard deviations (nonhomogeneity of variance tests) that detect no consistently significant performance differences between the two studies.

The multivariate technique was applied to the same data. The Hotelling's F-test statistic (ref. 1), for 6 and 23 degrees of freedom, was calculated to be 1.78, which is not significant even at the 10-percent significance level. Thus, all of the statistical analyses detect no differences in the functions, indicating that the refractive display system yields pilot performance that is equivalent to that obtained by using the reflective display system.

Comparison of Force-Feel Data Sets

Figure 4 depicts the mean sink rate at touchdown and standard deviations for groups of five touchdowns in chronological order by groups for the two force-feel cases. Both functions are data sets from the fixed-base simulator with the refractive lens display. The original control-loading parameter-set function (4.44 Hz undamped natural frequency) consisted of the data from two pilots, whereas the changed parameter-set function consisted of data from four pilots. Again, t-tests on pilot variability across the changed parameter-set data indicated no significant differences between the mean sink rates of the two pilots completing all runs, the two pilots who completed only the reflective runs, and the means of all four pilots.

Table V presents the results from the same conventional statistical procedures utilized earlier, although one-tailed tests are used for this comparison. The one-tailed tests utilize the alternative hypotheses that the means and variances of sink rate are larger for the changed force-feel parameter set than for the original set. The tests determine that the performance with the original force-feel parameters is superior. The Hotelling's F-test statistic, for 6 and 23 degrees of freedom, was calculated to be 2.36. This is found to be significant at the 93-percent confidence level. In reference 1, Myers cautions the user of modified profile analysis to be prepared to consider a test which is significant at a lower than usual level due to power considerations. Thus, the null hypothesis that the two functions are the same (i.e., force-feel characteristics have no effect) is rejected by the new technique also.

CONCLUDING REMARKS

The modification to the methodology of profile analysis to accommodate the testing of differences between two functions with a single test, rather than multiple tests at various values of the abscissa, has been described and demonstrated for two sets of simulation-performance data.

There were no significant differences in objective performance attributed to the change from the beam-splitter—reflective-mirror display system to the three-element refractive-lens display system. The objective measurements, therefore, agreed with the subjective opinions of the pilots.

The second application of the modified profile-analysis procedure did detect significant differences, as did conventional procedures. These differences were attributed directly to the differences in force-feel characteristics of the column. As demonstrated, the force-feel characteristics have an effect upon sink rate at touchdown.

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October 11, 1979

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TABLE I.- LINEAR APPROXIMATION OF THE FLIGHT

CHARACTERISTICS OF THE 737-100 AIRPLANE

Weight, N	400 341
Center of gravity	$0.31\bar{c}$
Flap deflection, deg	40
Landing gear	Down
Damping ratio for -	
Short period	0.562
Long period	0.089
Dutch roll	0.039
Period, sec, for -	
Short period	6.30
Long period	44.3
Dutch roll	5.12
Spiral divergence	24.0
Roll subsidence	0.53

TABLE II.- PERFORMANCE LIMITS OF VISUAL-MOTION SIMULATOR

Degree of freedom	Performance limits		
	Position	Velocity	Acceleration
Horizontal	Forward: 1.245 m Aft: 1.219 m	±0.610 m/sec	±0.6g
Lateral	Left: 1.219 m Right: 1.219 m	±0.610 m/sec	±0.6g
Vertical	Up: 0.991 m Down: .762 m	±0.610 m/sec	±0.8g
Yaw	$\pm 32^{\circ}$	$\pm 15^{\circ}$/sec	$\pm 50^{\circ}/\text{sec}^2$
Pitch	$+30^{\circ}$ -20°	$\pm 15^{\circ}$/sec	$\pm 50^{\circ}/\text{sec}^2$
Roll	$\pm 22^{\circ}$	$\pm 15^{\circ}$/sec	$\pm 50^{\circ}/\text{sec}^2$

TABLE III.- COMPARISON OF PITCH-AXIS CONTROL CHARACTERISTICS

Set	Damping	Undamped natural frequency, Hz	Force required to deflect 7.62 cm from trim, N	Breakout setting, joules
Original	1.0	4.44	115.65	Fore: 10.85 Aft: 1.36
Changed	0.4	1.37	71.17	Fore: 10.85 Aft: 1.36

TABLE IV.- STATISTICAL ANALYSES OF MEANS AND STANDARD DEVIATIONS FOR TWO DISPLAY SYSTEMS

Groups of five	Reflective-display sink rate, m/sec		Refractive-display sink rate, m/sec		t-test, two-tailed	F-test, two-tailed
	Mean	Standard deviation	Mean	Standard deviation		
1 to 5	1.44	0.58	1.88	0.35	2.20*	2.75(20,10)
6 to 10	1.19	0.37	1.56	0.64	2.02	2.99*(10,20)
11 to 15	1.37	0.39	1.69	0.46	2.00	1.39(10,20)
16 to 20	1.32	0.56	1.32	0.53	0	1.12(20,10)
21 to 25	1.34	0.34	1.15	0.30	1.50	1.28(20,10)
26 to 30	1.26	0.30	1.19	0.48	0.49	2.56(10,20)
n	20		10			

*Significant at the 5-percent level.
**Significant at the 2-percent level.

Tabulated two-tailed values		
Significance level	0.05	0.01
t, 28 degrees of freedom	2.05	2.76
F(10,20)	2.77	3.85
F(20,10)	3.42	5.27

TABLE V.- STATISTICAL ANALYSES OF MEANS AND STANDARD DEVIATIONS FOR

TWO FORCE-FEEL CHARACTERISTICS

Groups of five	Original sink rate, m/sec		Changed sink rate, m/sec		t-test, one-tailed	F-test, one-tailed
	Mean	Standard deviation	Mean	Standard deviation		
1 to 5	1.88	0.35	2.17	0.66	+1.29	3.56*
6 to 10	1.56	0.64	1.91	0.63	+1.43	0.97
11 to 15	1.69	0.46	1.83	0.54	+0.70	1.38
16 to 20	1.32	0.53	1.78	0.58	+2.10*	1.20
21 to 25	1.15	0.30	1.68	0.56	+2.78**	3.48*
26 to 30	1.19	0.48	1.74	0.86	+1.87*	3.21*
n	10		20			

*Significant at the 5-percent level.
**Significant at the 2-percent level.

Tabulated one-tailed values		
Significance level	0.05	0.01
t, 28 degrees of freedom	1.70	2.47
F(20,10)	2.77	4.41

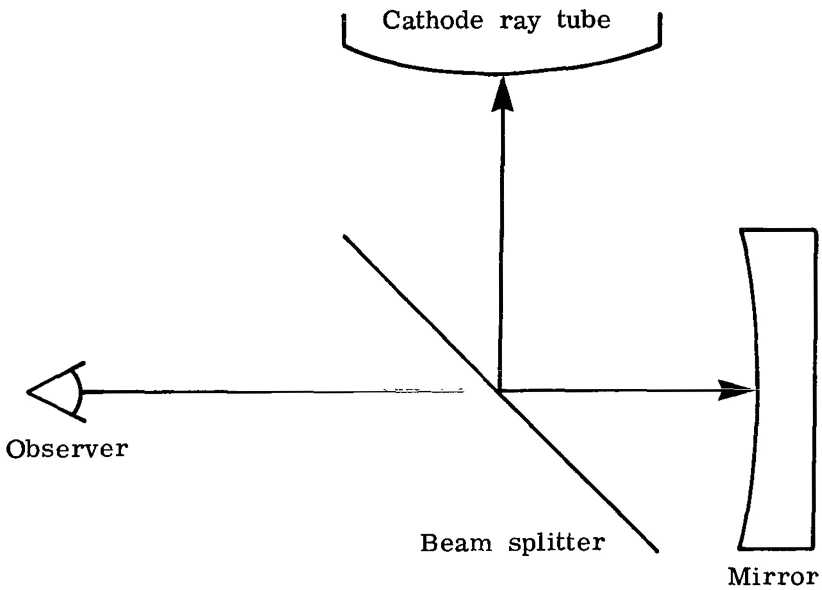

Figure 1.- Illustration of widely used reflective-type display system showing beam splitter and reflective mirror.

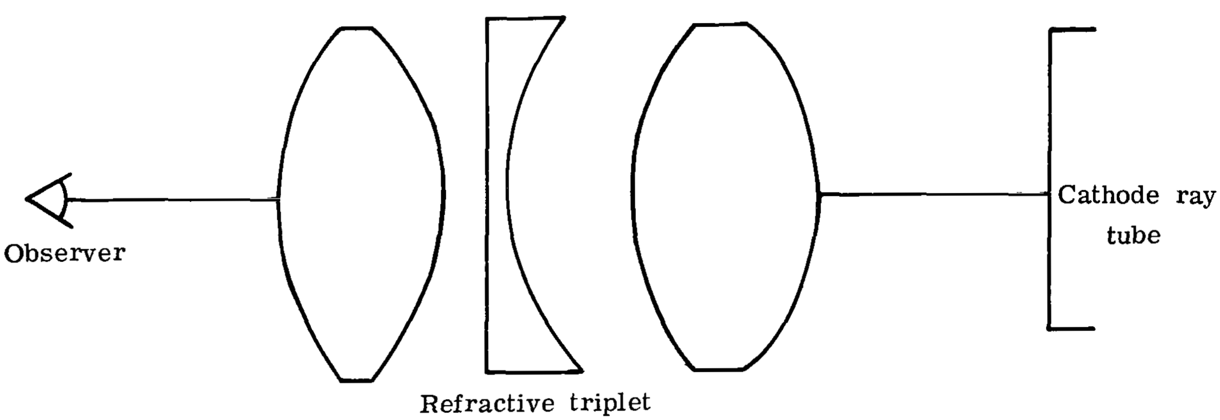

Figure 2.- Illustration of refractive virtual-image display system.

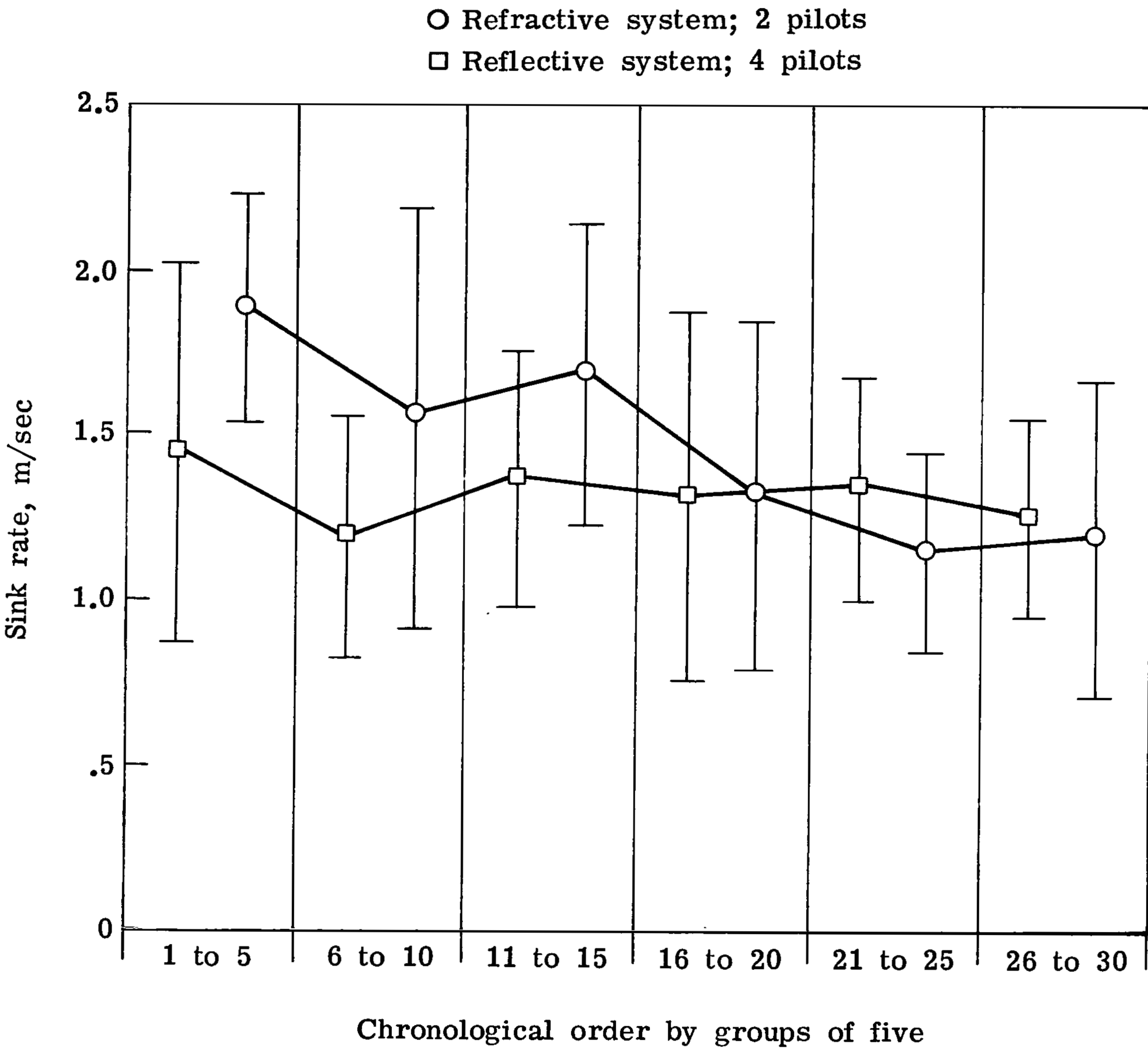

Figure 3.- Sink-rate comparison of the visual display systems.

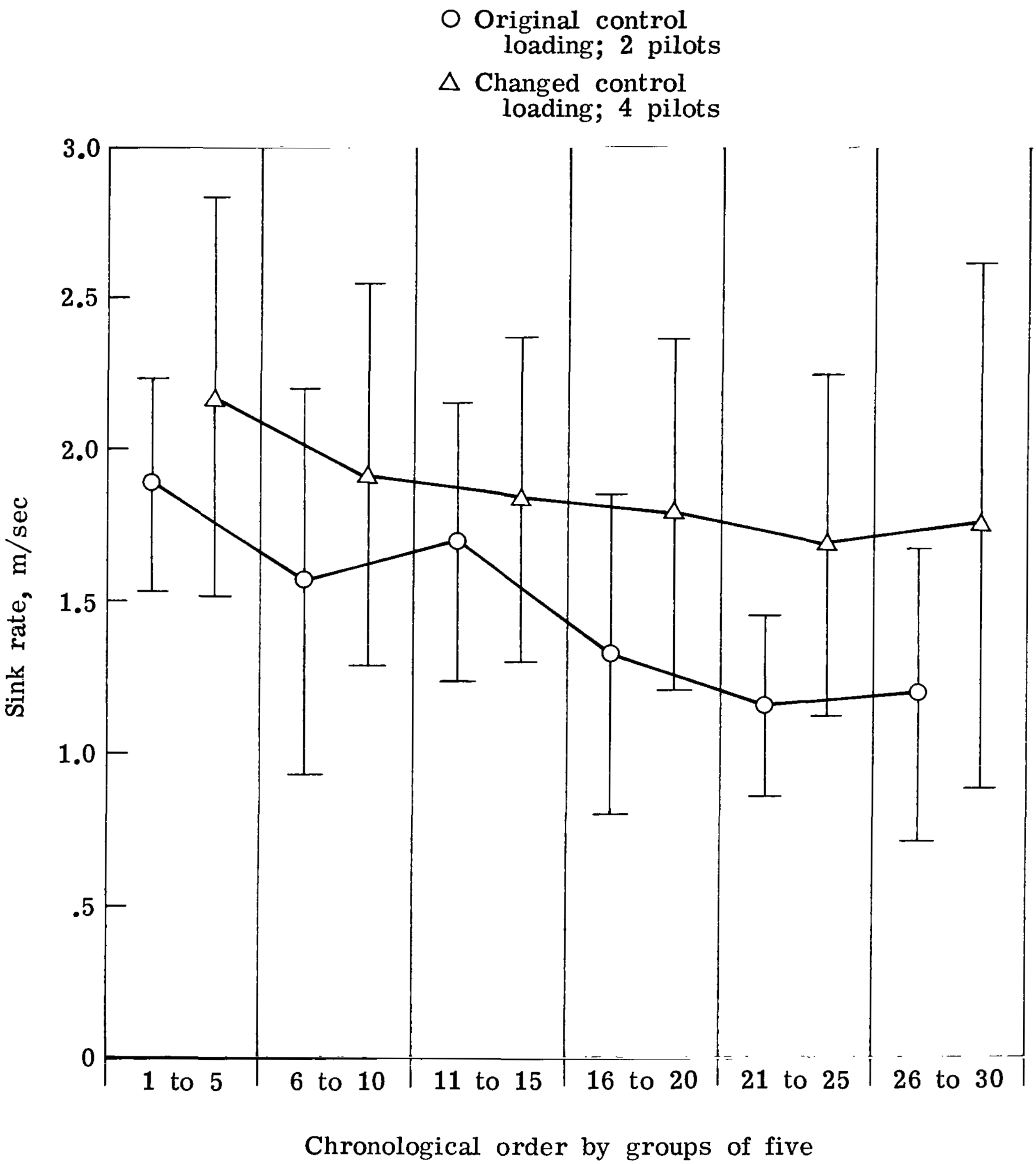

Figure 4.- Sink-rate comparison of the control-loading parameter sets.

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16. Abstract

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